Manifestation of nonlinear elasticity in rock: convincing evidence over large frequency and strain intervals from laboratory studies. Paul A. Johnson (EES-4, MS D443, Los Alamos National Laboratory, Los Alamos, NM 87545, USA *also at* Université Pierre et Marie Curie, Bureau des Mécaniques, Tour 22, 4, Place Jussieu, 75252 Paris Cedex 05, France) and Patrick N. J. Rasolofosaon (Institut Français du Pétrole, B. P. 311-92506, Rueil Malmaison Cedex, France)

Nonlinear elastic response in rock is established as a robust and representative characteristic of rock rather than a curiosity. This behavior is illustrated from a variety of experiments conducted over many orders of magnitude in strain and frequency. The evidence leads to a pattern of unifying behavior in rock: (1) Nonlinear response in rock is enormous. (2) The response takes place over a large frequency interval (dc to 10^6 Hz at least). (3) The response not only occurs, as is commonly appreciated, at large strains but also at small strains where nonlinear response and the manifestations of this behavior are commonly disregarded. Nonlinear response may manifest itself in a variety of manners, including a nonlinear stress-strain relation (hysteretic/discrete memory), nonlinear dissipation, harmonic generation, and resonant peak shift, all of which are related. The experiments described include: quasi-static stress-strain tests (strains of $10^{-4} - 10^{-1}$ at frequencies near dc – 1 Hz); torsional oscillator experiments (strains of $10^{-4} - 10^{-7}$, frequencies between 0.1 to 100 Hz); resonant bar experiments (strains of $10^{-4} - 10^{-8}$, frequencies between $10^3 - 10^4$ Hz); and dynamic, propagating wave experiments (strains of $10^{-6} - 10^{-9}$, frequencies between $10^3 - 10^6$ Hz). [Work supported by OBES/DOE through the University of California and the Institut Français du Pétrole.]

Number of words in abstract: 196
Suggested Special Session: Invited, Nonlinear acoustics of rocks
Technical Area: Physical Acoustics
(PACS) Subject Classification number(s): 43.25.Dc
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Special Facility: None.
Method of Presentation: Lecture.

Hysteresis in elastic behavior: the connection between low frequency response and acoustic properties of rocks. Katherine R. McCall (Earth and Environmental Sciences Div., Los Alamos Nat'l. Lab., Los Alamos, NM 87545), Robert A. Guyer (Dept. of Physics and Astronomy, Univ. of Massachusetts, Amherst, MA 01003), and Lei Zhu (Physics Dept., New Mexico State Univ., Las Cruces, NM 88003)

The strain response of rock to quasistatic stress cycles (e.g., 10^{-3} Hz) is highly nonlinear, hysteretic, and displays discrete memory. Rocks also display unusual nonlinear behavior in acoustic wave experiments (e.g., 10^{4} Hz). Nonlinearity and hysteresis are prominent features in elastic measurements on rocks. This observation is the key to making the connection between low frequency (quasistatic) and high frequency (acoustic) measurements, e.g., between static modulus and dynamic modulus. A new paradigm has been developed for the description of the elastic behavior of rocks and other consolidated materials. This paradigm uses the statistical properties of an ensemble of micron-scale hysteretic mechanical units to describe the elastic response of a macroscopic piece of material. It provides a recipe for inverting stress-strain data (low frequency data) for the distribution of hysteretic mechanical units. From this distribution, the high frequency acoustic response of the macroscopic piece of material can be predicted. The new paradigm will be described in principle and in application. Quasistatic stress-strain data on sandstone leads to predictions for dynamic modulus and resonant response that agree well with experiment.

Number of words in abstract: 196
Suggested Special Session: Invited, Nonlinear Acoustics of Rocks
Technical Area: Physical Acoustics
(PACS) Subject Classification number(s): 91.60.Ba, 91.60.Fe, 91.60.Lj, 83.80.Nb
Telephone number: 505-667-0463
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Method of Presentation: Lecture Only

Reflections on the nonlinear equation of state in rock based on experiment. James A. TenCate (EES-4 MS D443, Los Alamos National Laboratory, Los Alamos, NM 87545)

Measurements were made of the propagation of 1-D nonlinear waves (i.e., Young's mode) in a bar of Berea sandstone 3.8 cm in diameter and 1.8 m long. Both waveforms (time domain) and spectra (frequency domain) were measured. The experimental results were then compared with waveforms calculated from a numerical scheme based on the simple wave solution for 1-D waves in rock using a classical nonlinear equation of state. The numerical solution is written in Matlab and runs quickly on a small personal computer. Attenuation was added by propagating the waveform a small distance, transforming the waveform into the frequency domain and applying the attenuation, and then transforming back into the time domain and propagating the new waveform. The same method was applied earlier for nonlinear propagation of a sound wave in a tube of air by Pestorius and Blackstock. The experiments and simulations clearly demonstrate that a classical nonlinear equation of state is incomplete or inappropriate for describing or modelling nonlinear propagation in sandstone. Results from another model (Van Den Abeele, this session) suggest the same conclusions. [Work supported by OBES/DOE through the University of California.]

Number of words in abstract: 181
Suggested Special Session: Nonlinear acoustics of rocks
Technical Area: Physical Acoustics
(PACS) Subject Classification number(s): 43.25.Dc
Telephone number: (505) 665-6667
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Special Facility: None.
Method of Presentation: Prefer Lecture.

Elastic nonlinearity in rock: on the relative importance between higher order elastic constants and hysteresis. Koen Van Den Abeele, Paul Johnson, and James Ten Cate (EES-4 MS D443, Los Alamos National Laboratory, Los Alamos, NM 87545)

Rocks are extremely elastically nonlinear, even at strain as low as 10^{-7}. Recent simulations of dynamic elastic pulsed wave experiments and comparison with static and resonance test predictions revealed that the physical mechanism for nonlinearity in rocks cannot be attributed to higher order nonlinear coefficients alone. Static stress-strain tests and resonance measurements show in addition an undeniable hysteretic behavior of stress and modulus versus strain. Therefore, hysteresis has been introduced into the dynamic nonlinear wave equation by means of a discontinuous term in the modulus. The new theoretical model is based on four parameters: the first and second nonlinearity constants, attenuation and hysteresis strength. In doing so, rich harmonic spectra and nonlinear waveforms observed in dynamic pulse mode experiments can be simulated using realistic values of higher order elastic constants and hysteresis. Furthermore, the model provides characterization criteria for rock-types depending on the relative importance of hysteresis and nonlinearity parameters. Chalk, for instance, can have large first and second nonlinearity parameters because it shows a rich harmonic spectrum but no hysteresis. On the other hand, the nonlinear spectra of several sandstones can be attributed almost entirely to the first nonlinear coefficient and to hysteresis.[Work supported by DOE/OBES/UCal]

Number of words in abstract: 199
Suggested Special Session: Nonlinear acoustics of rocks
Technical Area: Physical Acoustics
(PACS) Subject Classification number(s): 43.25.Dc
Telephone number: (505) 665-9726
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Special Facility: None.
Method of Presentation: Prefer Lecture.

Experimental determination of the linear and nonlinear dynamic moduli of rock from quasistatic measurements. L. Zhu (Physics Dept., New Mexico State Univ., Las Cruces, NM 88003), R. A. Guyer (Dept. of Physics and Astronomy, Univ. of Massachusetts, Amherst, MA 01003), K. R. McCall (Earth and Environmental Sciences Div., Los Alamos Nat'l. Lab., Los Alamos, NM 87545), G. N. Boitnott (New England Research, Inc., White River Junction, VT 05001), L. B. Hilbert, Jr. (Dept. of Materials Science and Mineral Eng., Univ. of California, Berkeley, CA 94720), and T. J. Plona (Schlumberger-Doll Research, Ridgefield, CT 06877)

The central construct of a new theory of the elastic behavior of consolidated materials is the density in Preisach-Mayergoyz (PM) space. PM space is an abstract space in which the response of the mechanical units in the material to changes in stress state can be tracked. The theory provides a recipe for using quasistatic data to determine ρ_{PM}, the density of mechanical units in PM space. This recipe has been applied to quasistatic stress/strain data on 3 sandstones samples: (a) Berea I, (b) Berea II, and (c) Castlegate. The density of mechanical units ρ_{PM} was found for each sample. From ρ_{PM} the dynamic behavior of the samples can be predicted. Using the experimentally determined ρ_{PM} for each of the three samples the strain response to complicated stress protocols is predicted and the linear and nonlinear dynamic moduli of the samples are found as a function of pressure. The predictions agree well with experiments that test them.

Number of words in abstract: 172
Suggested Special Session: Nonlinear Acoustics of Rocks
Technical Area: Physical Acoustics
(PACS) Subject Classification number(s): 91.60.Ba, 91.60.Fe, 91.60.Lj, 83.80.Nb
Telephone number: 505-667-0463
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Special Facility:
Method of Presentation: Lecture preferred, poster ok